JOURNAL OF GEOPHYSICAL RESEARCH, VOL. 108, NO. C10, 3330, doi:10.1029/2002JC001735, 2003

Convective activity in the Labrador Sea: Preconditioning associated with decadal variability in subsurface ocean stratification

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Received 3 December 2002; revised 25 April 2003; accepted 4 August 2003; published 21 October 2003.

[1] The decadal variability of the convective activity in the Labrador Sea is investigated using 43 years of model output from a prognostic coupled ice-ocean model that simulates both the Arctic and the North Atlantic Oceans. The fields of the surface density and the mixed-layer depth indicate that the center of the convective activity is located in western Labrador Sea. The decadal variations of the convective depth are controlled to large extent by the oceanic preconditioning associated with changes in subsurface stratification. The intensity of the convective mixing varies from year to year, depending upon how strong the isopycnal doming is at the preconditioning stage at the center of the convective region. The variations of the subsurface stratification seem to be related to the subsurface temperature changes. *INDEX TERMS:* 1620 Global Change: Climate dynamics (3309); 4215 Oceanography: General: Climate and interannual variability (3309); 4255 Oceanography: General: Numerical modeling; *KEYWORDS:* decadal oscillation, North Atlantic, convection, Labrador Sea

Citation: Mizoguchi, K., S. L. Morey, J. Zavala-Hidalgo, N. Suginohara, S. Häkkinen, and J. J. O'Brien, Convective activity in the Labrador Sea: Preconditioning associated with decadal variability in subsurface ocean stratification, *J. Geophys. Res.*, *108*(C10), 3330, doi:10.1029/2002JC001735, 2003.

1. Introduction

[2] The Labrador Sea (LS) is a particularly interesting region of the ocean from a dynamic perspective. Here the deep water communicates with the sea surface via convection, which can significantly modify the meridional overturning circulation at the decadal timescales [*Holland et al.*, 2001]. Therefore the variations of the convective activity in the LS at the decadal timescales are expected to be closely linked to decadal variations in the North Atlantic. *Deser and Blackmon* [1993] showed that a 12- to 14-year decadal oscillation exists in the North Atlantic using the empirical orthogonal function (EOF) analysis technique applied to the sea surface temperature anomaly (SSTA) field. They also suggested a close link between the basin wide decadal oscillation and the variation of the ice concentration in the LS. *Mizoguchi et al.* [1999] demonstrated that alternating warm and cold SSTA propagate from the LS eastward with an approximate 14-year periodicity, using a propagating complex EOF analysis technique.

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0148-0227/03/2002JC001735$09.00

[3] The strong correlation between the SSTA and sea surface salinity anomalies (SSSA) inside the LS has been recognized in previous studies [*Drinkwater*, 1994; *Reverdin et al.*, 1997], and the variations of the SSSA are highlighted by the appearance of the Great Salinity Anomalies in the LS in the 1970s (GSA70s) and 1980s (GSA80s) [*Dickson et al.*, 1988; *Belkin et al.*, 1998]. During those years, extremely cold and fresh water anomalies occupied the surface layer and must have had a great impact on the intensity of convection. The decadal periodicity of the GSAs was first postulated by *Belkin et al.* [1998], who analyzed the GSA70s, documented the newly found GSA, and presented evidence of the GSA in the 1990s. The above anomalies peaked in the LS around 1971–1972, 1983–1984, and 1992–1994, respectively, implying a 10- to 11-year period [*Reverdin et al.*, 1997].

[4] Data from *Curry et al.* [1998] showed that there is low frequency variability in the Labrador Sea Water (LSW) thickness. It is directly translated to the intensity of the deep convection, with strong convection producing a thick layer and weak convection associated with relatively thin layer. According to the LSW thickness, the strong convection events occurred roughly in the early 1950s, 1960s, 1970s, and 1990s, indicative of a decadal oscillation. The strong correlation between the ocean surface and the subsurface seems to be closely associated with the decadal variability of the convective activity in the LS. Before discussing the dynamical process in convection at the decadal timescales, perhaps it is necessary to understand how it occurs at very short timescales as compared to decadal timescales, because the physical interpretation at the shorter timescales can

directly be applied to that at much longer timescales, as will be shown later on.

[5] One of the prominent features of convection is that it occurs in very localized regions of the northern North Atlantic. Observations [*Marshall and Schott*, 1999] suggested that there are certain conditions and specific locations that are common to deep-water formation. The surface water needs to be exposed to cold and dry strong winter winds to make it heavy enough to sink to greater depth. In this sense, the open ocean adjacent to boundaries is favored, at which the preferred atmospheric conditions are always supplied from the land or ice surfaces. The weakly stratified water beneath the seasonal thermocline must be brought up to the surface, immediately after the thermocline is eroded due to the surface mixing and cooling. The doming effect of the isopycnals, situated at the center of the cyclonic circulation in the LS, sets up the condition for the weakly stratified water from below to ventilate at the surface [*LabSeaGroup*, 1998].

[6] As discussed by *Killworth* [1976], there are basically three different phases in the convective processes. The first is preconditioning, which is followed by the second phase of violent mixing associated with surface cooling, during which vertically homogenized convective chimneys are established. Lastly, the sinking and spreading phase takes place. In the oceanic precondition, there are also three different spatial scales, i.e., plume [*Send and Marshall*, 1995], eddy [*Visbeck et al.*, 1996] and gyre scales. The first two are non-hydrostatic and have spatial scales of 100 m to 1 km and 5 km to 100 km, respectively. Baroclinic instability plays a major role at these scales. The gyre scale (50–1000 km) determines the large-scale factors that are subject to general circulation and vertical stratification patterns.

[7] Observations have shown that the spatial scale of a convective chimney in the LS is roughly O(100 km) [*Gascard and Clarke*, 1983] whereas that of atmospheric buoyancy forcing is O(500 km). This implies that the gyre-scale oceanic structure has something to do with the selection of a convection site, as well as the intensity of the penetration depth. The convective intensity may be already predetermined by the oceanic preconditioned state, or determined by the combination of both the ongoing buoyancy forcing and the oceanic background stratification before it.

[8] *Straneo and Kawase* [1999] compared the contribution to a subsequent convective event of localized buoyancy forcing and localized domed isopycnals in the preconditioned ocean. They showed the importance of both the buoyancy forcing and the oceanic preconditioning. *Alverson* [1995, chapter 4] used a simple one-dimensional mixed-layer model, with an exponentially increasing vertical density profile representing the domed isopycnals and a constant buoyancy forcing, to examine the doming effect of the oceanic background stratification on the intensity of convection. The results showed that with a constant buoyancy input stratification with more sharply domed isopycnals produces a deeper convective mixing.

[9] In this study, the investigation focuses mainly on large-scale convective phenomena related to the oceanic preconditioning in the LS using output from a coupled ice-ocean model. Attention is paid to the dynamical explanation of the convective activity. The model-produced variability of the mixed-layer depth is approximated by variability associated with the local buoyancy and subsurface stratification in the preconditioned ocean. It is further demonstrated that the decadal variability of the convective depth is strongly correlated to that of the subsurface ocean stratification. The decadal variation of the model may correspond to one of the natural modes of the decadal variability in the ocean.

[10] The model description and data are described in section 2, the results are shown in the context of other observations and compared to an analytical mixed-layer model in section 3. A summary and discussion follow in section 4.

4. Summary and Discussion

[33] A 43-year subset of output from a coupled ice-ocean model has been analyzed to study the decadal variability in the Labrador Sea (LS). The high surface densities or the deepest mixed layer in March, indicating the convective region, are located in the interior on the western part of the Labrador basin. Evidence of the decadal variability in the convective activity is seen in the temperature versus time diagram. Every year the mixing reaches a depth of at least 1000 m. Distinctively strong convective events occur from 1971 to 1972 and from 1983 to 1984, reaching depths greater than 2000 m. The modeled data reproduce the frequency of the convective events that are seen in the observations [*Lazier*, 1980; *Dickson et al.*, 1996; *Curry et al.*, 1998; *Dickson et al.*, 2002] relatively well at the decadal timescales.

[34] The cyclonic circulation in the LS sets up a favorable condition for deep convection, where the domed isopycnals play a role of oceanic preconditioning. The precondition in November significantly contributes to not only the determination of the convection site but also the convection depth. Sharply domed isopycnals near the surface increase the vertical density gradient there.

[35] An analytical one-dimensional mixed-layer model is used to diagnose the mixed layer depth (MLD) in March from the oceanic density profile in November and the external buoyancy forcing, and compare with the MLD directly obtained from the output of the coupled ice-ocean model in March. The one-dimensional mixed-layer model reproduces most of the variability, which is derived from the coupled ice-ocean model, in the convective depth in the LS at the decadal timescales (r = 0.85 at 0 lag). With a yearly varying oceanic density profile in November and the climatological buoyancy the model produces the decadal fluctuation considerably well (r = 0.73 at 0 lag). The decadal variability of the MLD is highly correlated to that of the subsurface ocean stratification at the preconditioning stage. The surface buoyancy forcing alone does not completely explain the decadal processes in the region of interest. Furthermore, the oceanic density profile, calculated from the yearly changing temperature and climatological salinity, has variability very similar to that of the model density, suggesting that the variability of the vertical stratification is associated with temperature changes in the subsurface ocean.